

# Full-Wave Effects in Coronagraph Masks



Daniel. J. Hoppe

Thomas A. Cwik

Jet Propulsion Laboratory

4800 Oak Grove Drive

Pasadena, CA 91109

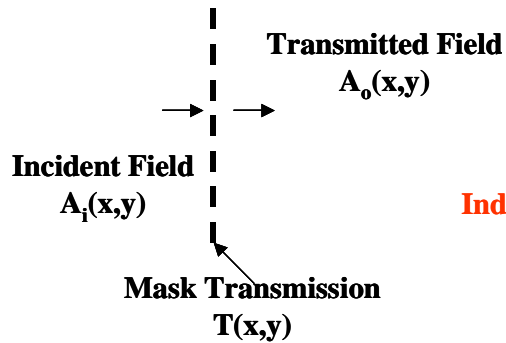
This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.



National Aeronautics and  
Space Administration

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

# Fourier Optics Analysis of Thin Masks



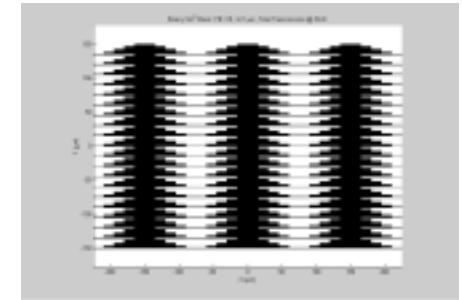
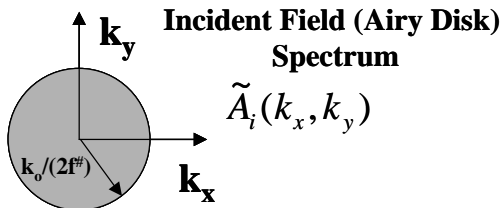
$$A_o(x, y) = A_i(x, y) \cdot T(x, y)$$

Assumes  $T(x,y)$  is  
Independent of  $A_i(x,y)$ , Independent of  $\lambda$ ,  
Independent of Polarization ... !  
[For Binary Masks  $T(x,y)=1/0$ ]

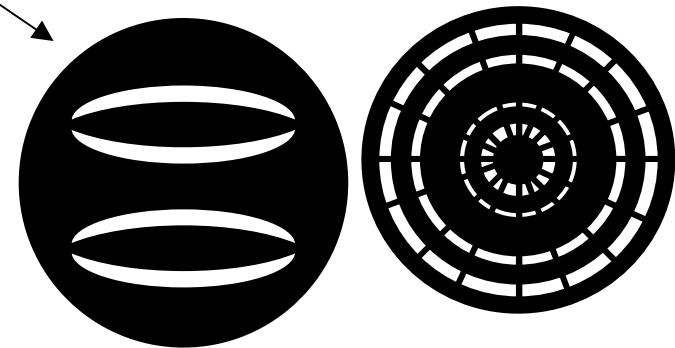
Fourier Transform of  $A_o$  is  
equivalent to the far field  
radiated toward the Lyot stop.

$$\tilde{A}_o(k_x, k_y) = \tilde{A}_i(k_x, k_y) \otimes \tilde{T}(k_x, k_y)$$

A convolution only for the simple  $T(x,y)$   
behavior assumed above!

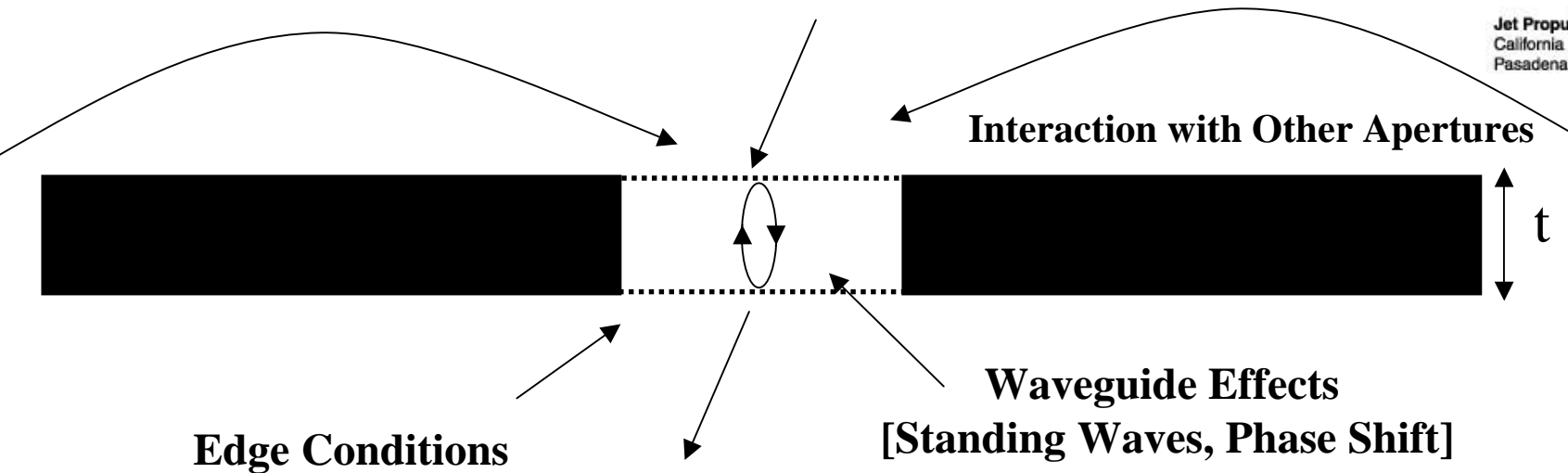


Binary Image-Plane Mask



Pupil-Plane Masks

# Full-Wave Electromagnetic Effects in Thick Masks



- Finite Conductivity of the Metal Layer
- Thickness of the Metal Layer [Due to Finite Conductivity]
- Dependence of the Transmission Coefficient on the Polarization of the Incident Field
- Dependence of the Transmission Coefficient on the Illumination Angle of the Incident Field
- Interaction Between Different Regions/Periods of the Mask
- Substrate Effects

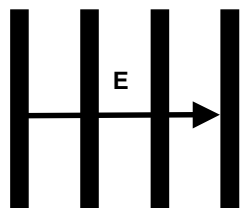
# Full-Wave Analysis of Masks

- Typical dimensions for a single period of the smallest structure of interest, a  $\text{Sin}^2$  binary image plane mask: For F/15 (considered a minimum):  $T_x=150\lambda$ ,  $T_y=15\lambda$ , and Thickness= $0.6\lambda$ . [Large EM Problem!]
- Goals
  - Estimate the smallest acceptable F# for the binary image-plane masks to function properly [smallest allowable feature sizes?]
  - Estimate cross-polarization levels introduced by the masks
  - Estimate bandwidth effects/limitations
- Two-Pronged Approach
  - Pursue exact analysis using available solution techniques: GTD/UTD, FDTD, MOM, FMM, ...
  - Consider several types of approximate analysis
    - Obtain order-of-magnitude estimates for EM effects
    - Use in “Local”, approximate analysis of a real mask
    - Compare various mask types against each other
    - Example problems
      - Canonical Problem: thick periodic gratings
      - Approximate propagation through thick apertures using modal expansion

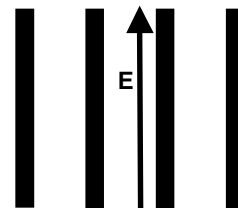
# Thick Periodic Grating

- Why a Thick Periodic Grating?
  - Thick One-Dimensional Grating will Demonstrate Propagation Effects of Gap Size and Incident Polarization
  - Periods of 30-100 $\lambda$  ( $F\# = 30-100$ ) Translate into a Reasonable EM Problem for which a Converged Result can be Obtained
  - Both the Periodic and Non-Periodic Binary Masks Appear as A Thick Periodic Grating when Examined Locally and will Share many of the Grating's EM Effects
  - Grating Transmission Coefficients can be used in an Approximate Analysis of the Binary Mask

# Canonical Example: Thick Strip Grating, Relative Transmission Versus Gap Dimension, $30\lambda$ Period

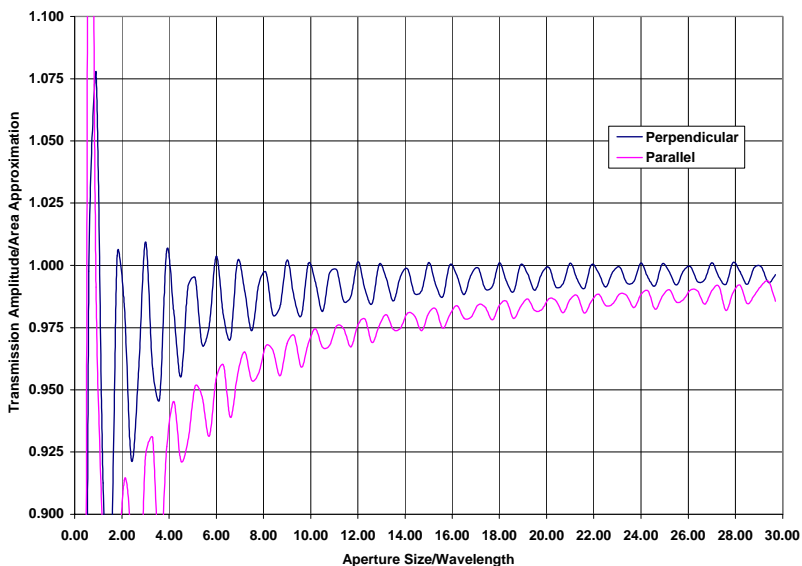


Perpendicular  
Polarization

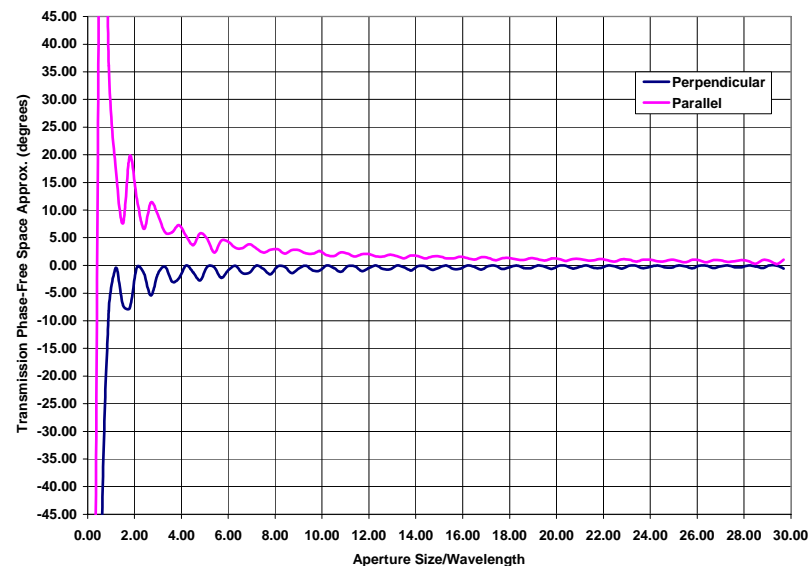


Parallel  
Polarization

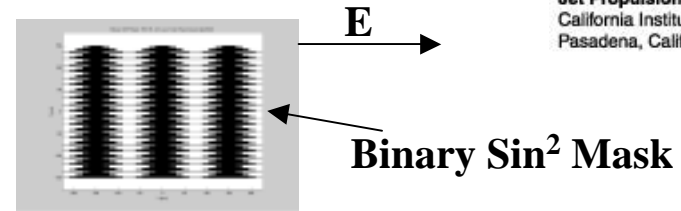
Relative Transmission (0.6 lambda Thick Strip Array, Period=30 lambda)



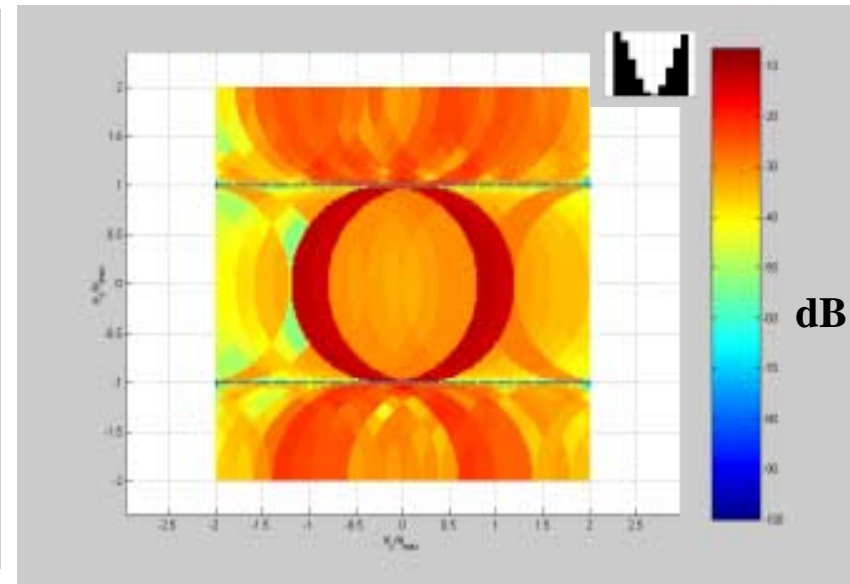
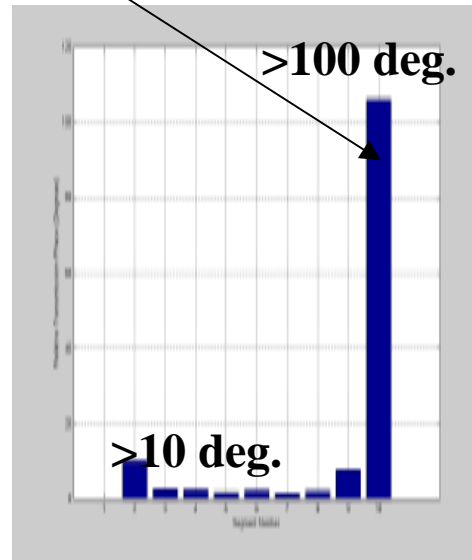
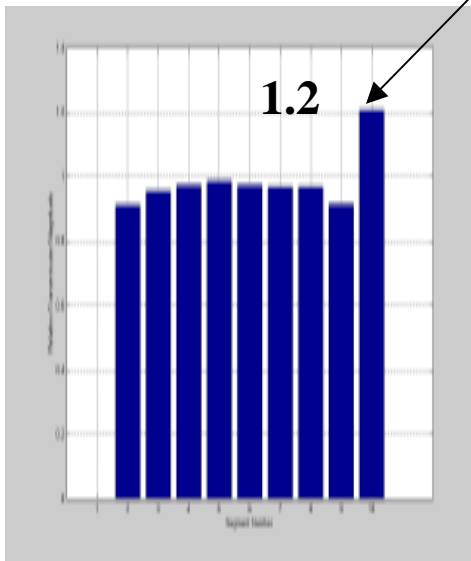
Relative Transmission (0.6 lambda Thick Strip Array, Period=30 lambda)



# Approximate Mask Performance Using Parallel Plate Transmission Coefficients in the Gaps



Smallest Gap



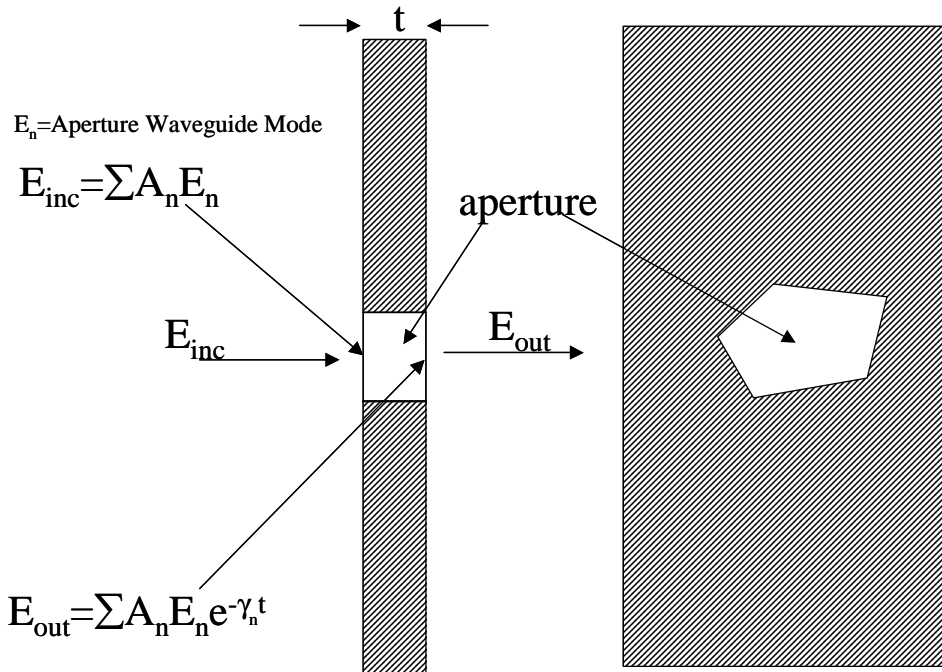
Relative Amplitude

Relative Phase

F/15 Approximate Transmission Coefficients

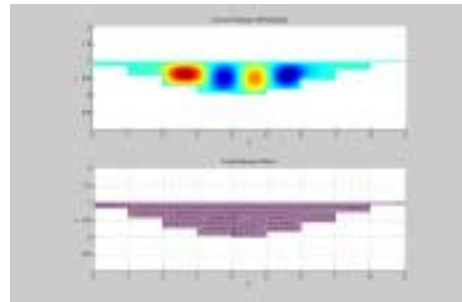
Approximate Lyot Stop Fields  
 F/15 Contrast @  $5\lambda/D \approx 60$  dB  
 Other Polarization (not shown)  $\approx 68$  dB  
 F/30 Results  $\approx 69/80$  dB

# Approximate Propagation Through a Thick Aperture

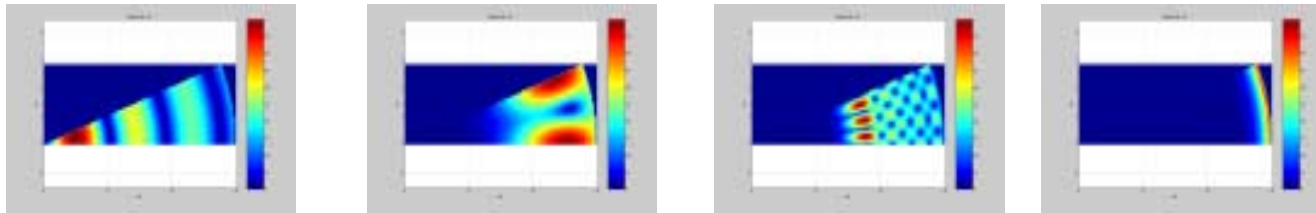


- Determine Waveguide Modes of the Aperture (analytic/FEM)
- Expand Incident Electric Field Into This Modes Set
- Ignore Magnetic Field
- Propagate/Decay Modes Through the Aperture
- Evaluate Field at Aperture Exit
- Estimates: Phase and Amplitude Throughout Aperture and Cross-Polarization
- Exact Solution Adds Magnetic Field Match and Reflected Modes in Aperture

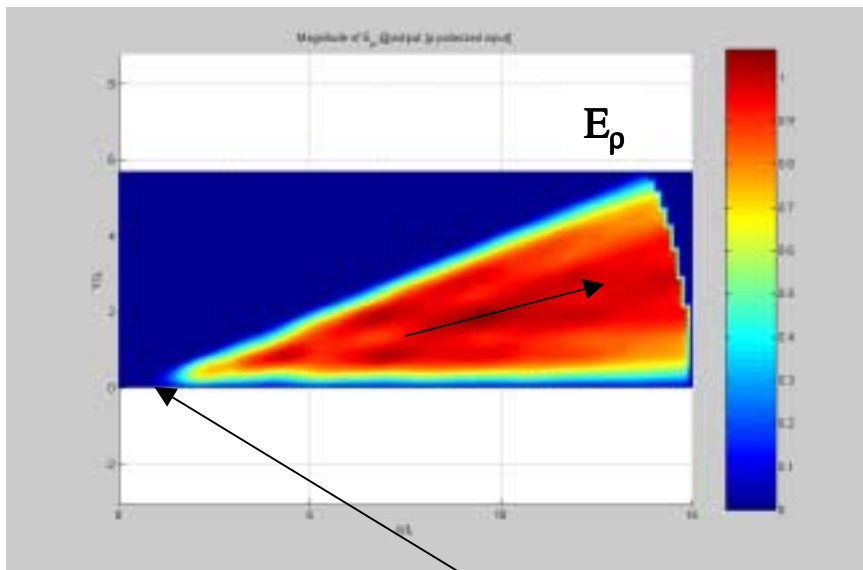
Example Aperture Mode  
 $\text{Sin}^2$  Binary Mask



# Analytic Example: Sector-Shaped Aperture, $\rho$ -Directed Incident Field

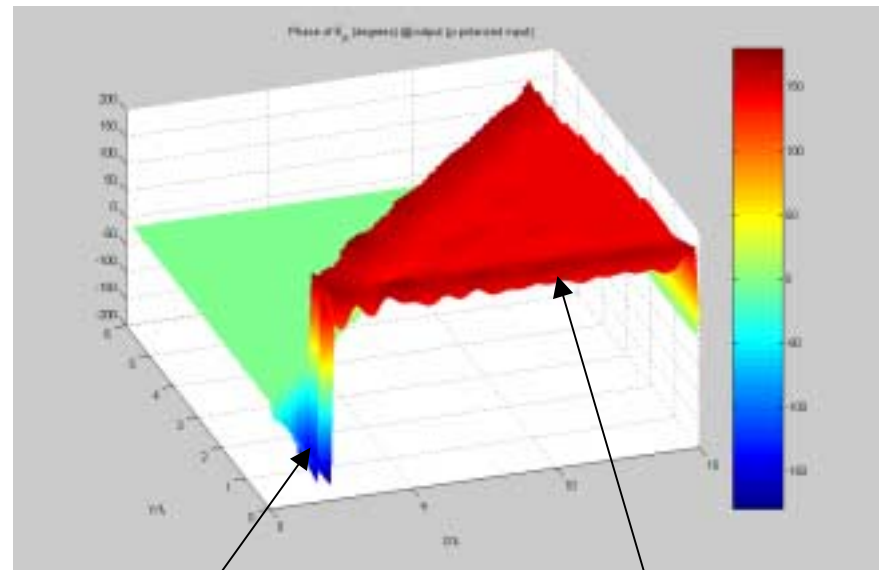


**Example  
Modes**



**Magnitude**

Pinched-Off Region

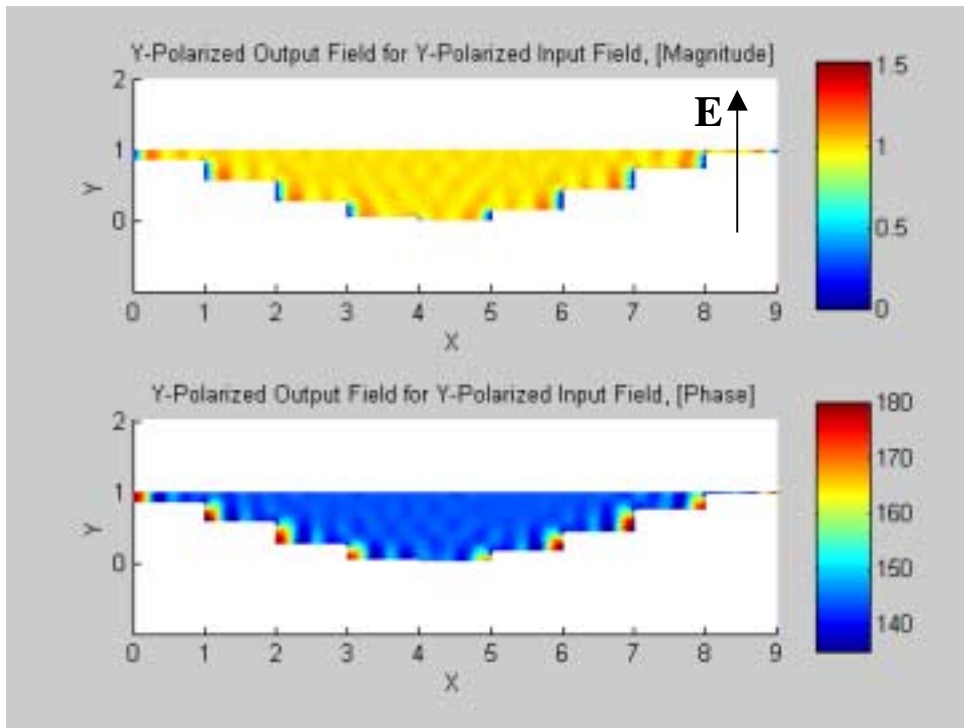


**Phase**

Phase Errors  
Near Edge

# Small-Scale Example

## Binary $\text{Sin}^2$ Mask



Single Cell of 2-D Periodic Structure  
Must Transform to Find Lyot  
Stop Fields

- Small Scale Example (F/3), Illustrates Full-Wave Effects
- Aperture Size  $30\lambda \times 3\lambda$
- Thickness  $0.6\lambda$
- Y (Perpendicular) Polarization
- FEM Solution/Modal Expansion into 300 Waveguide Modes
- Visible Effects:
  - High-Order Phase/Amplitude Ripple [OK if Rapid Enough]
  - Distortion/Shorting of Field Near PEC Edges [Effective Area]
  - Cross Polarized Field Near Internal Corners (not shown here)
- This Work is On-Going